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Influence of Velocity Shear on the Rayleigh-Taylor Instability

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The influence of a transverse velocity shear on the Rayleigh-Taylor instability is investigated. It is found that a sheared velocity flow can substantially reduce the growth rate of the Rayleigh-Taylor instability in the short wavelength regime (i.e., $kL > 1$ where L is the scale length of the density inhomogeneity), and causes the growth rate to maximize at $kL < 1.0$. Applications of this result to ionospheric phenomena [equatorial spread F (ESF) and ionospheric plasma clouds] are discussed. In particular, the effect

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20. Abstract (Continued)

of shear could account for, at times, the 100's of km modulation observed on the bottomside of the ESF ionosphere and the km scale size wavelengths observed in barium cloud prompt striation phenomena.

CONTENTS

INFLUENCE OF VELOCITY SHEAR ON THE RAYLEIGH-TAYLOR INSTABILITY

I. Introduction

An important instability in a variety of geophysical phenomena is the Rayleigh-Taylor instability. The instability is an interchange instability and is driven primarily by an opposing density gradient and gravitational force (e.g., a heavy fluid supported by a light fluid). In a magnetized plasma, the mode exists in both the collisionless and collisional regimes. However, in many regions of interest, such as the ionosphere, the plasma can also contain inhomogeneous velocity flows transverse to the magnetic field. In fact, in the absence of other effects (such as gravity, density gradients and collisions), this sheared flow can give rise to a transverse Kelvin-Helmholtz instability (Mikhailovskii, 1974). The purpose of this letter is to investigate the influence of velocity shear on the Rayleigh-Taylor instability (Drazin, 1958; Chandresekhar, 1961).

We find that velocity shear can have a dramatic effect on the Rayleigh-Taylor instability. Namely, for a sufficiently strong velocity shear, the growth rates of the most unstable modes (i.e., those such that $kL > 1$ where L is the scale length of the inhomogeneity) are substantially reduced; leading to maximum growth in the regime $kL < 1$. Thus, velocity shear has the effect of preferentially exciting a long wavelength mode of the Rayleigh-Taylor instability which is in sharp contrast to the behavior of the mode in the absence of velocity shear. This result may explain the long wavelength oscilllations (i.e., several hundred kms) of the bottomside F layer during equatorial spread F (Tsunoda, 1981a; Tsunoda and White, 1981; Kelley et al., 1981) and the early time structuring of injected barium clouds in the ionosphere (Simons et al., 1980; Wescott et al., 1980).

The scheme of this letter is as follows. In the next section we present the basic equation which describes the influence of velocity shear on the Rayleigh-Taylor instability. In Section III, the various instabilities are discussed (i.e., Rayleigh-Taylor, Kelvin-Helmholtz and the generalized Rayleigh-Taylor). Finally, in the last section, we discuss the application of our results to ionospheric phenomena, i.e., equatorial spread F and plasma cloud striations.

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II. Theory

The geometry of the plasma and field configuration used in the analysis are as follows. We consider $\underline{B} = B_o \hat{e}_z$, $\underline{g} = g \hat{e}_x$, $n = n_o(x)$ and $\underline{V} = - V_o(x) \hat{e}_y$. We also include ion-neutral collisions ($\nu = \nu_{in}$) in the theory so that both collisionless and collisional instabilities are considered.

The basic assumptions used in the analysis are as follows. We assume perturbed quantities vary as $\delta p \sim \delta p(x) \exp(iky-i\omega t)$ with $\omega \ll \Omega_i$ and $kr_{Li} \ll 1$ where Ω_i is the ion gyrofrequency and r_{Li} is the mean ion Larmor radius. We neglect perturbations along the magnetic field ($k_\parallel = 0$) so that only two dimensional mode structure in the xy plane is obtained. We assume $\nu_{in} \ll \Omega_i$ which is consistent with ionospheric F region conditions. Ion inertial effects are retained in the analysis, but electron inertial effects are neglected. We assume quasi-neutrality so that $n_e \approx n_i = n$.

A key feature of our analysis is that a nonlocal theory is developed. That is, the mode structure of the potential in the x-direction is determined by a differential equation rather than an algebraic equation obtained by Fourier analysis. This technique allows one to study modes which have wavelengths larger than the scale size of the inhomogeneities (i.e., $kL < 1$ where L represents the scale length of the boundary layer). In fact, this is crucial to describing the Kelvin-Helmholtz instability produced by a transverse velocity shear (Mikhailovskii, 1974).

Based upon the assumptions discussed above, the fundamental equations used in the analysis are

$$\partial n_\alpha/\partial t + \nabla \cdot (n_\alpha \underline{V}_\alpha) = 0 \qquad (1)$$

$$0 = \underline{E} + \frac{\underline{V}_e \times \underline{B}}{c} \qquad (2)$$

$$m_i(\partial/\partial t + \underline{V}_i \cdot \nabla)\underline{V}_i = e\underline{E} + \frac{e\underline{V}_i \times \underline{B}}{c} - m_i \nu_{in} \underline{V}_i + m_i \underline{g} \qquad (3)$$

where α denotes species (e,i: electron, ion). We substitute $\underline{E} = - \nabla\phi$,

$\underline{V} = \underline{V}_o(x) + \delta\underline{V}$ and $n = n_o(x) + \delta n$ into Eqs. (1)-(3). Here, ϕ is the perturbed potential. We find the perturbed velocities to be

$$\delta\underline{V}_e = (c/B)\,[-ik\phi\,\hat{e}_x + (\partial\phi/\partial x)\,\hat{e}_y] \tag{4}$$

and

$$\delta\underline{V}_i = (c/B)\,\left[-i\left(1 + \frac{1}{\Omega}\frac{\partial V_o}{\partial x}\right)^{-1} k\phi + \frac{\tilde{\omega} + i\nu_{in}}{\Omega}\frac{\partial\phi}{\partial x}\right]\hat{e}_x + (c/B)\,\left[\frac{\partial\phi}{\partial x} - \frac{\tilde{\omega} + i\nu_{in}}{\Omega}\,k\phi\right]\hat{e}_y \tag{5}$$

where $\Omega = \Omega_i = eB/m_i c$ and $\tilde{\omega} = \omega - kV_o$. Substituting Eqs. (4) and (5) into Eq. (1), we arrive at the following equation

$$\frac{\partial^2\phi}{\partial x^2} + p\,\frac{\partial\phi}{\partial x} + q\,\phi = 0 \tag{6}$$

where

$$p = \frac{\partial \ln n_o}{\partial x}\left(1 - \frac{i\nu_{in}}{\tilde{\omega} + i\nu_{in}}\,\frac{kV_o}{\tilde{\omega}}\right) \tag{7}$$

$$q = -k^2 + \frac{kV_o}{\tilde{\omega} + i\nu_{in}}\left[\frac{1}{V_o}\frac{\partial^2 V_o}{\partial x^2} + \frac{gk}{\tilde{\omega}V_o}\frac{\partial \ln n_o}{\partial x} + \frac{\partial \ln V_o}{\partial x}\frac{\partial \ln n_o}{\partial x} - \frac{i\nu_{in}}{\tilde{\omega}}\left(\frac{1}{n_o}\frac{\partial^2 n_o}{\partial x^2} + \frac{\omega}{\tilde{\omega}}\frac{\partial \ln n_o}{\partial x}\frac{\partial \ln V_o}{\partial x}\right)\right] \tag{8}$$

In obtaining Eq. (6) we have made use of the quasi-neutrality condition, assumed $\partial V_o/\partial x \ll \Omega_i$ and have retained ion inertial terms to order ν_{in}/Ω_i.

III. Results

To highlight the influence of velocity shear on the Rayleigh-Taylor instability we first consider two limiting cases: (1) the Rayleigh-Taylor instability with no velocity shear and (2) the Kelvin-Helmholtz instability with no collisions, gravity or density gradient. Following this we discuss a general solution of Eq. (6).

A. Rayleigh-Taylor instability

We take $V_o = 0$ so that Eq. (6) becomes

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial \ell n n_o}{\partial x}\frac{\partial \phi}{\partial x} - k^2\left[1 - \frac{g}{\omega + i\nu_{in}}\frac{1}{\omega}\frac{\partial \ell n n_o}{\partial x}\right]\phi = 0 \quad (9)$$

Equation (9) can be easily solved in the local approximation (i.e., $k^2L^2 >> k_x{}^2L^2 >> 1$ where $L = (\partial \ell n n_o/\partial x)^{-1}_{x=x_o}$.) we have assumed $\phi(x) \propto \exp(ik_x x)$). We obtain the dispersion equation

$$\omega^2 + i\nu_{in}\omega - g/L = 0 \quad (10)$$

which has the solution (Hudson and Kennel, 1975; Haerendel, 1974)

$$\omega = -\frac{i\nu_{in}}{2}\left[1 \pm (1 - 4g/L\nu_{in}^2)^{1/2}\right] \quad (11)$$

Instability can occur when $g/L < 0$ (i.e., g and L are oppositely directed). The collisionless and collisional solutions are

$$\omega = \pm\, (g/L)^{1/2} \qquad \nu_{in} << (4g/L)^{1/2} \quad (12)$$

$$\omega \approx -i\,(g/L)\,\nu_{in}^{-1} \qquad \nu_{in} >> (4g/L)^{1/2} \quad (13)$$

We now solve Eq. (9) numerically for a density profile $n = n_o \exp(-x^2/2L^2) + \Delta n$. The results are shown in Fig. 1 (curve A) which is a plot of $\gamma/(g/L)^{1/2}$ vs. kL for $\Delta n/n_o = 0.01$ and $\nu_{in}/(g/L)^{1/2} \approx 0.5$. As expected, the growth rate maximizes in the regime $kL >> 1$. However, note that the maximum growth rate $(\gamma/(g/L)^{1/2} \approx 1.1)$ is slightly larger than that predicted from local theory ($\gamma/(g/L)^{1/2} = 1.0$ from Eq. (11)). This is due to the Gaussian-like density profile chosen for the numerical example.

B. Kelvin-Helmholtz instability

We assume $V_o(x) \neq 0$ but take $\nu_{in} = 0$, $g = 0$ and n_o = const. Equation (6) becomes

$$\frac{\partial^2 \phi}{\partial x^2} - [k^2 - \frac{k\partial^2 V_o/\partial x^2}{\omega - kV_o}] \phi = 0 \qquad (14)$$

which is well-known (Mikhailovskii, 1974). Note that in the local approximation

$$\omega = kV_o + k^{-1}(\partial^2 V_o/\partial x^2)_{x=x_o} \qquad (15)$$

so that the mode is stable. In general, an instability can occur only when $(\partial^2 V_o/\partial x^2)_{x=x_o} = 0$ where $x_1 < x_o < x_2$, and x_1 and x_2 are the boundaries (Rayleigh's theorem). As an example, we assume an equlibrium velocity profile $\underline{V}_o = V_o \tanh(x/L)\, \hat{e}_y$. The solution to Eq. (14) is shown in curve B of Fig 1 where $\gamma/(V_o/L)$ vs. kL is plotted. The instability is purely growing (i.e., $\omega_r = 0$) and only occurs in the regime $0 < kL < 1$. Maximum growth occurs at $kL \simeq 0.5$ with $\gamma \simeq 0.18\, (V_o/L)$ (Michalke, 1964).

C. Generalized Rayleigh-Taylor instability

We now consider the general case where both the standard Rayleigh-Taylor and the Kelvin-Helmholtz instablities coexist (Drazin, 1958). Since the wavelength regimes of these two instabilities are distinct from one another (i.e., Rayleigh-Taylor favors $kL > 1$ while Kelvin-Helmholtz favors $kL < 1$), one might think that these "modes" do not affect one another in the linear regime. However, this is not the case as is shown by curve C of Fig. 1. Here, we solve Eq. (6) for the following profiles: $n = n_o \exp(-x^2/2L^2) + \Delta n$ and $\underline{V}_o = V_o \tanh[(x-x_o)/L]\, \hat{e}_y$ with $\nu_{in}/(g/L)^{1/2} = 0.5$, $V_o/(gL)^{1/2} = 1.0$, $\Delta n/n_o = 0.01$ and $x_o/L = -2.0$. Note that the scale lengths of the density and velocity gradients are assumed equal. The position of the sheared velocity flow is chosen to coincide with the localization region of the Rayleigh-Taylor instability. As in curve A, we plot $\gamma/(g/L)^{1/2}$ vs. kL and it is found that the growth rate maximizes at $\gamma \approx 0.4\,(g/L)^{1/2}$ for $kL \approx 0.7$ over the range considered ($0 < kL < 10$). The most dramatic feature of including velocity shear in the analysis is the strong reduction in the growth rate of modes in the short wavelength regime (i.e., $kL > 1$). Thus, the main influence of velocity shear on the Rayleigh-Taylor instability is to suppress the most unstable waves, those with $kL > 1$, and to maximize growth in the long wavelength regime ($kL < 1$).

This effect of velocity shear on the Rayleigh-Taylor instability can be easily seen from local theory. For simplicity, we consider Eq. (6) in the limit $k^2L^2 >> k_x{}^2L^2 >> 1$ and $\nu_{in} = 0$. The dispersion equation becomes

$$\hat{\omega}^2 - k^{-1}\left(\frac{\partial^2 V_o}{\partial x^2} + \frac{\partial \ln n_o}{\partial x}\frac{\partial V_o}{\partial x}\right)\hat{\omega} - g\,\frac{\partial \ell n n_o}{\partial x} = 0 \qquad (16)$$

where $\partial^2 V_o/\partial x^2$, $\partial V_o/\partial x$ and $\partial \ell n n_o/\partial x$ are defined locally at some point $x = x_o$. Writing $\partial^2 V_o/\partial x^2 = V_o''$, $\partial V_o/\partial x = V_o'$ and $\partial \ell n n_o/\partial x = 1/L$, the solution to Eq. (16) is

$$\hat{\omega} = \frac{1}{2k}\left(V_o'' + V_o'/L\right) \pm \frac{1}{2}\left[(V_o''/k + V_o'/kL)^2 + 4g/L\right]^{1/2} \qquad (17)$$

In the limit $V_o'' \rightarrow 0$ and $V_o' \rightarrow 0$, Eq. (11) is recovered. However for V_o'', $V_o' \neq 0$ the velocity shear term is clearly stabilizing. Moreover, the stabilizing influence is k dependent and we expect that as k increases the influence of velocity shear becomes weaker. Qualitatively this result is shown in Fig. 1 (curve C); the most strongly suppressed modes have $kL \approx 1$ and growth increases as kL increases, albeit small. However, owing to the crude approximation made in obtaining Eq. (17), good quantitative agreement cannot be expected.

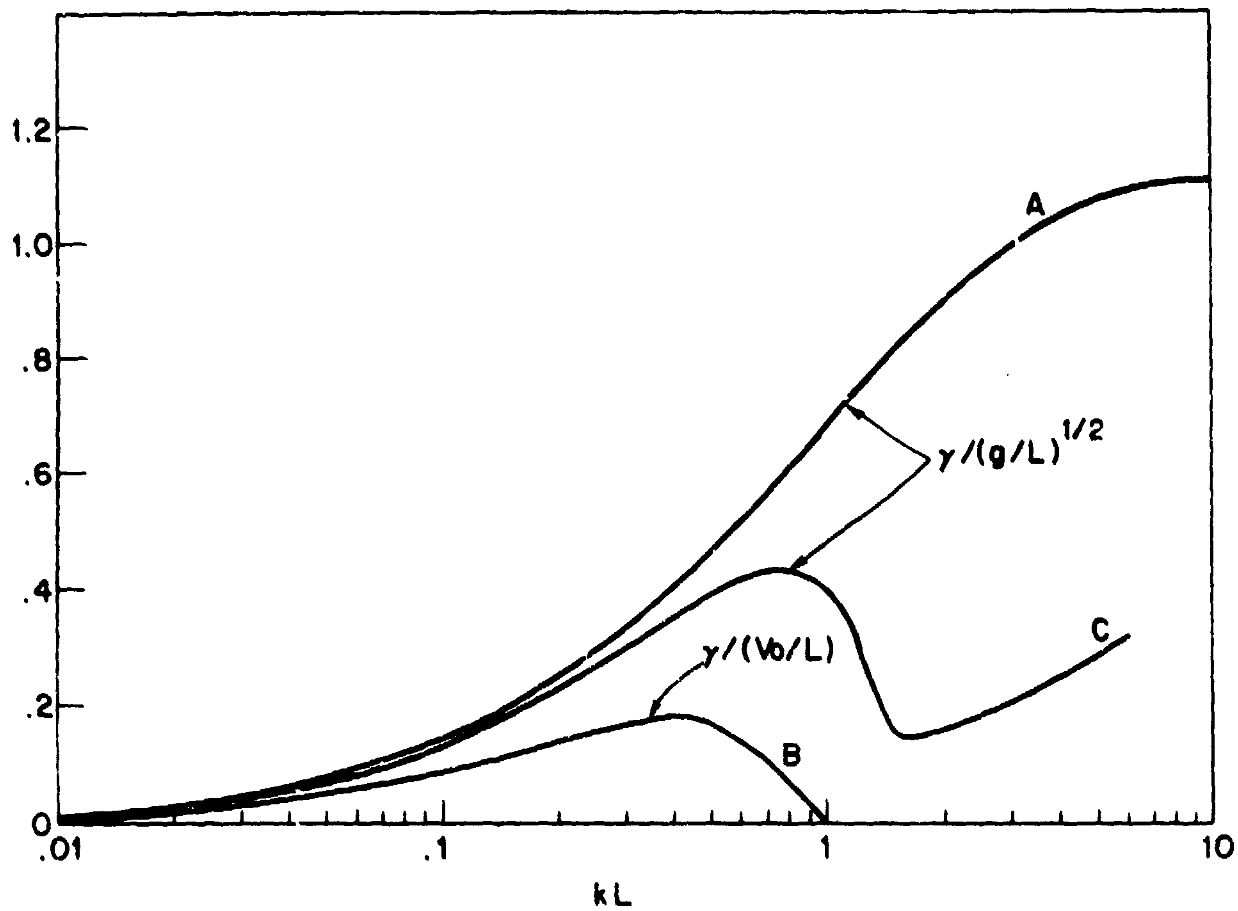

Figure 1

Plots of the growth rate (γ) vs. kL under various conditions. The profiles used are: $n = n_0 \exp(-x^2/2L^2) + \Delta n$ and $V = V_0 \tanh[(x - x_0)/L]$. (A) Rayleigh-Taylor instability with no velocity shear. Here, $\gamma/(g/L)^{1/2}$ vs. kL is plotted and we have assumed $\nu_{in}/(g/L)^{1/2} = 0.5$ and $\Delta n/n_0 = 0.01$. (B) Kelvin-Helmholtz instability with no density gradient, collisions and gravity. Here, $\gamma/(V_0/L)$ vs. kL is plotted. (C) Generalized Rayleigh-Taylor instability including velocity shear. Here $\gamma/(g/L)^{1/2}$ vs. kL is plotted. We have assumed $\nu_{in}/(g/L)^{1/2} = 0.5$, $V_0/(g/L)^{1/2} = 1.0$, $\Delta n/n_0 = 0.01$ and $x_0/L = -2.0$.

IV. Discussion

We have investigated the influence of velocity shear on the Rayleigh-Taylor instability. Our analysis includes gravity, density and velocity inhomogeneities and ion-neutral collisions. In general, the Rayleigh-Taylor instability is most unstable in the regime $kL > 1$ where L characterizes the inhomogeneity scale length. On the other hand, the Kelvin-Helmholtz instability, driven by a sheared transverse velocity flow, is unstable for $kL < 1$. In the presence of a sufficiently strong velocity shear, the short wavelength spectrum ($kL > 1$) of the Rayleigh-Taylor instability is strongly suppressed and a maximum in growth occurs for $kL < 1$. Thus, velocity shear may cause a long wavelength mode to be preferentially excited; whereas in the absence of velocity shear the dominant wave mode usually has a shorter wavelength determined by initial conditions or nonlinear processes. We now discuss two possible applications of this theory to ionospheric phenomena: equatorial spread F and ionospheric plasma cloud striations.

It is believed that the Rayleigh-Taylor instability can play a major role in the onset of equatorial spread F (see for example Ossakow, 1979; Fejer and Kelley, 1980). After sunset, the density gradient on the bottomside of the F layer steepens which initiates the Rayleigh-Taylor instability. However, there are also observations of (1) velocity shears existing in the F region during spread F (Kudeki et al., 1981; Tsunoda et al., 1981) and (2) long wavelength (i.e., several hundred kms) oscillations on the bottomside of the F layer (Tsunoda and White, 1981; Kelley et al., 1981). From our theory we expect velocity shear to preferentially excite the Rayleigh-Taylor instability at $kL \approx 0.7$. If we take $L = 25$ km for the bottomside of the F layer then the most unstable wavelength occurs at $\lambda \sim 250$ km which is comparable with observations ($\lambda_{obs} \sim 600$ km Kelley et al., 1981; $\lambda_{obs} \sim 400$ km Tsunoda and White, 1981; $\lambda_{obs} \sim$ tens to a few hundred kms, Tsunoda, 1981b). Also, the magnitude of the velocity shear necessary for this is $V_o/L \approx 2 \times 10^{-2}$ Hz which is somewhat larger than, although comparable with, observational values (Kudeki et al., 1981) which are $V_o/L \sim 2 \times 10^{-3}$ Hz. Thus, the influence of velocity shear on the Rayleigh-Taylor instability may explain the long wavelength oscillations of the bottomside of the F layer. We mention that gravity waves have also been proposed as a mechanism to generate these oscillations (Kelley et al., 1981).

Several aspects of the theory need further comment concerning this application to equatorial spread F. First, the velocity shear profile used in the calculation is based on observational data and not on a self-consistent equilibrium model. An equilibrium which provides the observed shear flows is beyond the scope of this paper. One possible mechanism to generate the velocity shear is via a neutral wind in the equatorial F region when the F layer is electrically coupled to a background E layer away from the equatorial region (Zalesak et al., 1981). It is interesting to note that when such a coupling occurs, the plume strtuctures are tilted away from the vertical (Zalesak et al., 1981). Thus, the tilt of the plumes can be regarded as a measure of the coupling between the E and F regions, and therefore, as a measure of sheared velocity flows in the F region. Observationally, the largest amplitude, long wavelength oscillations occur when the plumes are strongly tilted (Kelley et al., 1981). This suggests that sheared velocity flows may play a role in their development. Second, the relative positions of the density and velocity profiles play a crucial part in the "interaction" of the velocity shear and the Rayleigh-Taylor instability. The strongest effect of shear occurs when the velocity shear is a maximum in the localization region of the Rayleigh-Taylor mode. Finally, collisions can destroy the local maximization of the growth rate in the long wavelength regime if they are sufficiently strong. This indicates that velocity shear will be more important at high altitudes (> 400 km) in affecting the Rayleigh-Taylor instability.

Artificial plasma clouds (e.g., barium releases) in the ionosphere are subject to a complex and dynamic evolution. One of the more notable characteristics is the striating of the clouds, i.e., "fingers" forming on one side of the cloud (Rosenberg, 1971; Davis et al., 1974). In many cases these striations can be explained by the $\underline{E} \times \underline{B}$ gradient drift instability (Linson and Workman, 1970; Zabusky et al., 1973; Scannapieco et al., 1976). However, recent shaped charge releases develop striations very rapidly (Simons et al., 1980; Wescott et al., 1980) and these initial striations cannot be explained by the $\underline{E} \times \underline{B}$ drift instability because of its relatively slow growth rate. Simons et al. (1980) have proposed a kinetic instability driven by an ion ring distribution to explain the prompt striations in the Buaro release. However, it is unclear that a kinetic instability can produce the large density perturbations necessary to explain the structuring of the cloud. An alternative mechanism has been proposed by Pillip (1971) and Fedder (1980) which is based upon an interchange instability; this instability is similar to the Rayleigh-Taylor instability, but relies upon the deceleration of the cloud (Scholer, 1970) rather than gravitational acceleration. An inhomogeneous electric field can exist at the edges of the cloud due to polarization charges which produce a sheared transverse velocity flow (Sydora et al., 1981). Thus, our theory can be applied to the structuring of barium releases which are injected across the magnetic field. If the boundary layer is several hundred meters thick ($L \sim 100$ - 300 m) then from $kL \approx 0.7$ we obtain wavelengths $\lambda \sim 1 - 3$ km which are consistent with observations. Moreover such a layer thickness yields substantial growth rates according to Fedder's model ($\gamma \sim 10\ \mathrm{sec}^{-1}$). This final example is largely suggestive at this time, yet is sufficiently encouraging that further investigation is warranted.

In conclusion, we have shown that a sheared transverse velocity flow can have a pronounced effect on the Rayleigh-Taylor instability. For a sufficiently strong velocity shear, the short wavelength spectrum of the instability is suppressed and growth maximizes at $kL < 1.0$ where L is the scale length of the inhomogeneity. This result may explain the long wavelength oscillations of the bottomside of the F layer during equatorial spread F and the prompt structuring of injected barium clouds. We emphasize that this is a preliminary report and that a more detailed analysis (i.e., parameteric variations) will be presented in a future paper.

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